SIMULATION OF PWM INVERTER FED AND VECTOR CONTROLLED INDUCTION MOTOR DRIVES

A pre Dissertation submitted to the

RAJIV GANDHI PROUDYOGIKI VISHWAVIDYALAYA, BHOPAL

in partial fulfillment of the requirements for the award of the degree

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MASTER OF TECHNOLOGY
IN
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by

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प्रपत्र

(एम.ई./एम.टेक./एम.फार्म छात्रों हेतु)

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हस्ताक्षर शपथग्रहिता

<u>गाईड एवं संचालक/प्राचार्य द्वारा सत्यापित किया जावे</u>

सत्यापित करते हैं कि छात्र/छात्रा का नाम ..... नामांकन क्रमांक .....
..... द्वारा उपरोक्तानुसार भरी गयी जानकारी प्रमाणित एवं सही है।

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संस्था का कोड: .....

दूरभाष क्रमांक .....

दिनांक .....

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ABSTRACT

Simulation of adjustable speed drives using Induction motors can be done by two methods viz. PWM and Vector control Technique. When closed loop is considered for the PWM fed Induction motors, the value of speed which is fed back to the motor in the terms of torque, the waveforms of stator current, rotor speed and electromechanical torque has been seen on the scope, Now, by making the use vector control technique, the same waveforms can be seen on the scope and also FFT analysis for the two methods can be done. The speed becomes constant earlier in vector control than PWM fed Induction motor drive and also the THD can be improved by vector control method.

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List of Symbols, Abbreviations and Nomenclature

SPWM	Sinusoidal Pulse Width Modulation
PMSM	Permanent Magnet synchronous motors
THD	Total Harmonic Distortion
FOC	Field Oriented Control
SFG	Signal Flow Graph
3-Φ supply	Three Phase Supply
Te	Electromagnetic Torque
Is	Stator current
ωm	Synchronous Speed
V	Voltage
Hp	Horse Power
ASD	Adjustable Speed Drive
Ls	Self Inductance
Lr	Rotor Inductance

DTC	Direct Torque Control
Lm	Mutual Inductance
Id	Direct axis current
Iq	Quadrature axis current
T	Sampling Time
σ	Rotor leakage flux
τ	Time constant
ωr	Rotor speed

CHAPTER-1
INTRODUCTION

1.1 INTRODUCTION

Adjustable Speed drives are needed in various applications. The application of adjustable speed drive will lead to the harmonics present in the current. It creates power grid pollution and it also leads to electromagnetic interference into the atmosphere. Quality of power and electromagnetic interference are the main constituents of electrical Induction motor drives. These type loads are distributed almost over an electrical network. Harmonics are not desirable in this type of interference with electrical equipments because it will result in unacceptable level of distortion of voltage.

Harmonic calculations needs unique equipments, which are quite expensive and they are not easily available in the market. My paper investigates the modeling and simulation of an induction motor for an adjustable speed drive and the analysis of harmonics is also done here. Using ac drives and ac motors have the plus point of lesser maintenance, more speeds and lesser size. Compared to dc drives, the higher cost of ac drives is in part compensated by a lower ac machine cost. Compared to uncontrolled ac motors, supplied by a regular grid, the efficiency of inverter controlled drives can be vastly optimized by, e.g. flux optimization. The simulation of Adjustable speed drives can be done by two methods for calculating Total Harmonic Distortion i.e. Pulse Width Modulation fed Induction motor and Vector control technique. The resulting energy saving, which depends on the respective application, may be beneficial for the power system.

1.2 ADJUSTABLE SPEED DRIVE

Adjustable speed drive (ASD) or variable-speed drive (VSD) describes equipment used to control the speed of machine. Where speeds may be selected from several different pre-set values, usually the drive is said to be adjustable speed. If the output speed can be changed without steps over a range, the drive is usually referred to as *variable speed.*

An adjustable speed drive might consist of an electric motor and controller that is used to control the motor's operating speed. The combination of a constant-speed motor and a continuously

adjustable mechanical speed-varying device might also be called an adjustable speed drive. Power electronics based variable frequency drives are rapidly making older technology obsolete.

1.2.1 Induction Machine

Induction motor can be operated in one direction or both the directions. It depends upon the necessity of drives Per-phase equivalent circuits are mostly in use in steady-state method and designing of an ac machines which are not suitable to get the dynamic performance of the motor. A dynamic model is necessary to analyze vector control of ac motor drives A big goal was achieved in the study of three-phase ac machines through the development of the reference frame theory.

The machine model can be transformed from one to another reference frame by using these techniques It is quite possible to give the simplicity to the complexity of mathematical induction machine model by choosing the reference frame theory In earlier days, these techniques were invented for the analysis and simulation of ac machines, but nowadays they are being rapidly used in the digital control of those machines. The necessity for compact machine models is there as digital control technology is used to control torque ,current and flux of ac motors. The induction motor is mostly used in the industries because of its self starting feature, lower cost, reliable and rugged structure these motors are generally used where fast dynamic response is not necessary With the application of vector control it is possible to control the induction motors to achieve dynamic performance comparable to that of dc motors The dynamic model of Induction machine is necessary because it helps to understand the vector control. The torque - speed characteristics are easily explained by the dynamic model equations which are created on rotating reference frame

1.2.2 Induction motor operation

An induction motor is only a part of an adjustable speed drive assembly. As such the 1nduction Machine is fed from power electronics converter (PEC), but indirectly in most cases from the power grid. Induction machine has smooth speed of operation due to its robustness. There are two types of Induction motor according to its rotor construction i.e. Squirrel Cage and Wound rotor motor or slip ring machine. The work of this thesis depends on working of squirrel cage Induction Motors. The principle of operation is based on electromagnetic induction. Squirrel

Cage rotor has copper bars and electromotive force and torque produced due flux changing in stator magnetic field and due to mutual inductance rotor rotates with slip speed. Slip is the difference between stator magnetic field to the rotor speed.

Based on the JxB force principle, three operation modes of IM are easily identified

(With Ns – Synchronous speed, N – Rotor speed):

• Motoring: N < Ns; N and Ns either positive or negative.

• Generating: N > Ns; N and Ns either positive or negative.

• Braking: (N>0 & Ns <0) or (N<0 & Ns >0).

An adjustable speed drive consists of rectifier and inverter that form AC to DC converter. Its functioning depends on the joint action of the rectifier and the inverter and then convert dc to controllable AC which is fed to Induction motor drive.

1.2.3 Rectifier

The rectifier is a six pulse full-wave diode bridge type rectifier (p=6), It is shown in the form of a universal bridge in the simulation circuit. It converts the power supply ac voltage into dc voltage with a few ripple. Traditional modeling for controlled rectifiers is a time-delay element in the s-domain.

Rectified dc voltage has mean voltage which is slightly less than peak line voltage due to voltage drops in the power switches and ripple frequency of 300 Hz. To reduce the THD of the input current, the main obstacles are the gaps in the current, present during the time intervals when the phase voltage of the considered phase is neither minimum nor maximum among the phase voltages, causing both of the diodes connected to that phase to be reversed bias

1.2.4 DC link

The DC link is also called DC bus The diodes in the rectifier convert the input sinusoidal ac voltage to a rectified dc which is then smoothed down by the dc link in order to produce a dc voltage with lower ripples. It also acts as energy source to supply the inverter when the supply fails. ASD immunity against disturbances therefore depends on the energy stored in the circuit and energy demanded by the load.

DC link is represented with an inductance L and a shunt capacitance C. Representation of the DC link filter is essential for the proper simulation of ASDs. It is the filter that makes the VSD harmonic current waveforms different from those of the direct current drives.

1.2.5 Inverter

The inverter is controlled by the PWM scheme. In a sampling interval T= 1/ f_c, the pulse width angle can be changed once. Therefore the PWM inverter is working in the discrete state. The purpose of the inverter is to convert the low ripple dc voltage to adjustable ac voltage to allow the speed variation of an induction motor. The PWM inverter cannot be considered as a proportional element. Since its output voltage can't be controlled once the pulse width is applied, it should be looked as a sample and time-varying element. The simulations of the ASD under normal operation and under vector control are shown respectively.

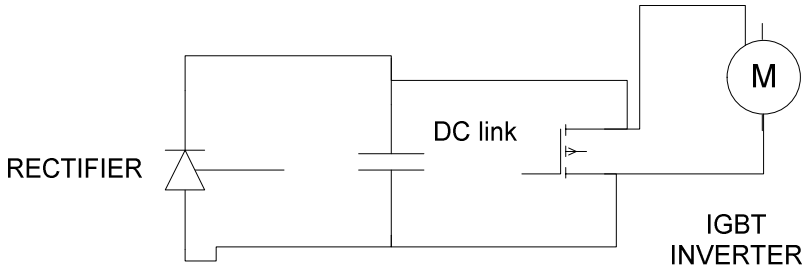

Fig1.1 Schematic diagram of Adjustable Speed Drive

The basic concept of vector control is to separate the components of stator current responsible for production of flux and the torque. The vector control is obtained by the magnitude, frequency and the phase of the stator current by the control of inverter . Since the control is obtained by controlling both the phase angle and magnitude of current this method of controlling is called vector control.

1.3 CONCEPT OF HARMONIC

A harmonic is a component of periodic wave having frequency which is an integral multiple of the fundamental power line frequency of 50 Hz. The fundamental wave is pure sine wave without any distortion. The 2nd harmonic differs in frequency and amplitude from the fundamental wave. It has two times the frequency and half the amplitude of the fundamental

wave. The 3rd harmonic has three times the frequency and one-third the amplitude of the fundamental wave. Fig1.2 depicts the fundamental, 2nd and 3rd harmonic. Since any periodic waveform f(t) can be expressed as a Fourier series, it follows that the sum of OC, the fundamental, the second harmonic, and so on, must produce the waveform f(t).

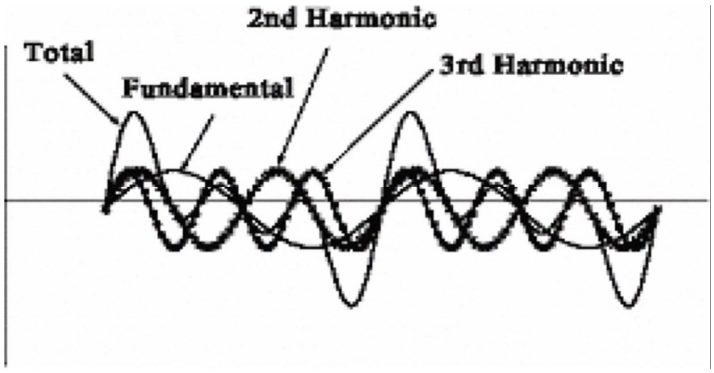

Fig1.2 Summation of fundamental, second and third harmonic [**1**]

The most widely used index for measuring the harmonic content of a given waveform is the total harmonic distortion (THD). It is a measure of the effective value of a waveform and may be applied to either voltage or current.

Total harmonic distortion is the contribution of all the harmonic frequency currents to the fundamental. Just as waveforms can be added to produce distorted waves, distorted waves may be decomposed into fundamental and harmonic components.

Total Current Harmonic Distortion (THD) - The THD is a measure of the effective value of the harmonic components of a distorted waveform. This index can be calculated for either voltage or current. The following equation gives total harmonic distortion for voltage.

$$\frac{\sqrt{(V2^2 + V3^2 + V4^2 \ldots\ldots\ldots\ldots V\infty^2)}}{V1}$$

The THD provides an idea about how much extra heat will be realized when a distorted voltage is applied across a resistive Load.

1.4 PULSE WIDTH MODULATION

Pulse-width modulation uses a rectangular pulse wave whose pulse width is modulated resulting in the change of the average value of the waveform**.** Pulse-width modulation (PWM), or pulse-duration modulation (PDM), is a commonly used method for controlling power to inertial electrical devices, made practical by modern power electronic switches. A triangular wave having very high frequency is compared with sinusoidal wave; the resultant wave is fed to the IGBT (insulated gate Bipolar transistor) inverter for switching purposes. It has a fast response and simulation of ASD come under normal operation. Figure 3 shows the schematic diagram for PWM fed ASD.

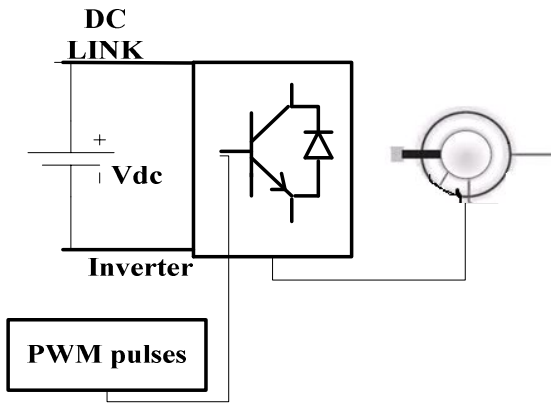

Fig1.3 Schematic diagram of PWM fed Adjustable Speed drive

1.5 VECTOR CONTROL TECHNIQUE

The main objective of vector control is to achieve greater performance under torque and speed change. For vector control of induction motor its model is considered in a synchronously rotating d-q reference frame. The basic concept of vector control is to separate the components of stator current responsible for production of flux and the torque. The vector control is obtained by the magnitude, frequency and the phase of the stator current by inverter control. Since the control is obtained by controlling both the phase angle and the magnitude of current, this method of control is called vector control.

In vector control, an alternating current induction or synchronous motor is controlled under all operating conditions like a separately excited DC motor. That is, the AC motor behaves like a

DC motor in which the field flux linkage and armature flux linkage created by the respective field and armature (or torque component) currents are orthogonally aligned such that, when torque is controlled, the field flux linkage is not affected, thus enabling the dynamic torque response.

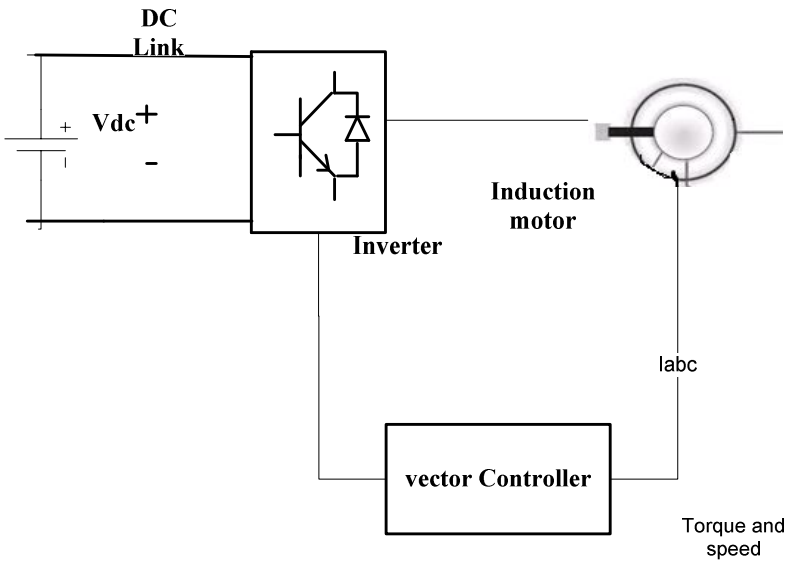

Fig1.4 Schematic diagram of Adjustable Speed Drive

1.6 COMPARISON OF PWM AND VECTOR CONTROL TCHNIQUE

The total current harmonics distortion is reduced in vector control technique in comparison to the PWM fed inverter used in ASD. By evaluation of the harmonic distortion spectra of PWM inverter fed ASD and Vector controlled ASD it is clear that harmonic distortion levels fall considerably to a lower value under Vector control scheme.

1.7 OUTLINE OF THE THESIS

Chapter 1 deals with the Introduction about the work which has been done in this thesis.

Chapter-2 deals with the Literature Review which I have done for the thesis

Chapter-3 deals with the Induction motors and adjustable speed drives

Chapter -4 deals with Total Harmonic Distortion

Chapter -5 deals with Pulse Width Modulation

Chapter 6 deals with Vector controlled Induction Motor Drives.

Chapter-7 deals with the simulation and result which are using MATLAB/SIMULINK environment in previous unit.

Chapter-8 deals with conclusion and future work scope which has to be done in future by making the use of this method.

References-10 deals with the reference that taken for the purpose of research work that are the part of the chapter.

CHAPTER-2
LITERATURE REVIEW

T.Kartik, R.Kameswara Rao, **et.al.[**1] This paper describes the adjustable speed drives. Adjustable speed drive is becoming a significant load component for distribution of power. It involves the usage of an Induction motor (1M). This paper involves the modeling and control of an Induction motor and also investigates its effects on the total current harmonic distortion of the adjustable speed alternating current drives. The simulation was carried out with the help of the Simulink toolbox available in Matrix laboratory. The power quality issue has become more important due to the ever increasing number of non-linear loads. The low frequency harmonic currents which are produced by such nonlinear loads can cause harm to the power system appliances. It is important to desing these loads to suppress the problems arising from harmonic pollution. This paper includes simulation of adjustable speed drives such that power quality is improved.

Bhim Singh,, *G.* Bhuvaneswari, Vipin Garg *and* Sanjay Gairola, et.al [2] This paper studied an autotransformer with less kilo volt ampere rating for twenty four pulse ac to dc converter fed vector controlled induction motor drives (VCIMDs) is presented for harmonic current suppression. The twenty four pulse operation is obtained by using dc ripple reinjection technique in twelve pulse ac to dc converters. The proposed new harmonic suppressor is found capable of suppressing up to twenty first harmonic in the supply current. The method for the designing of such an autotransformer for proposed ac to dc converter is presented to show the flexibility in the design for making it a cost effective substitute suitable for various applications, where presently a six pulse diode bridge rectifier is used. The effect of load variations on Vector controlled induction motor drive are also studied to show the effectiveness of the proposed converter.

Bhim Singh, Sanjay Gairola, et.al [3]

In this paper, an autotransformer based thirty six pulse AC to DC converter fed vector controlled induction motor drives (VCIMD's) is presented for reduction of harmonic-currents. A thirty six pulse converter is realized using a specially designed autotransformer and two eighteen pulse diode bridge rectifiers. The effect of load variations on Vector controlled induction motor drive is also identified to demonstrate the effectiveness of the proposed AC to DC converter. A set of power quality indices on input alternating current mains and on direct current bus for a VCIMD fed from six pulse and eighteen pulse AC to DC converters are also given to compare their performance. It is concluded that input current total harmonic distortion (THD) less than five percent is possible with the proposed technique. The polygon autotransformer which is used for proposed thirty six pulse AC to DC converter system have small ratings and needs only two inter phase reactors unlike the eighteen pulse AC to DC converter where three such type of reactors are needed. The resulting system has shown a high level of performance with clear power characteristics to be used in uncontrolled front-end rectifiers.

Viktor Kremer, Zi Qiang Zhu and Dave Howe, et.al [4]

In this paper, Both vector control and direct torque control are used in variable-speed ac drive systems, particularly for induction machine drives. This paper explains the application of both the control techniques to a two-phase permanent magnet machine supplied from a full H-bridge inverter, with space vector modulation being employed to get variable-amplitude, variable-frequency, two-phase sinusoidal voltages. The direct torque control (DTC) strategy controls the flux and thrust force by means of an active and reactive force estimator, by making the use of active and reactive power. It is shown that as compared to vector control, DTC is more effective for the compensation of the influence of cogging force

Pavel Brandstetter, Ondrej Francik† and Petr Simonik, et.al [5]

In this paper, Results of the sensor less control of alternating current drive with the permanent magnet synchronous motor is presented. The method is based upon the rotor magnetic flux components calculation. Practical realization was made by the microcomputer control system with the digital signal processor TMS320F2812. The graphical representation of the electrically controlled drive was made in the software Lab View. The measured results of proposed

laboratory experiments with applied vector control and sensor less vector control is shown at conclusion

Yunguo Zhu , Xing Zhang[1] Shengyong Liu et.al [6]

This paper explains the Brushless Doubly-Fed Machine (BDFM), which does not make use of the brush and slip ring, improves security and reliability. The BDFM is supposed to have a good future as an alternating current drive system or variable-speed constant-frequency power generation system. Vector control is widely studied in the BDFM, but the information of rotor speed and position must be calculated. This paper presents speed sensor less vector control system for Brushless doubly fed machine. Double synchronous speed two-axis rotating coordinate mathematical model based on model references which is quite adaptive to speed identification theory. Vector control model in Matrix laboratory/Simulation environment is designed with stability theory. The simulation results verify that this system has good both the stationery and dynamic characterstics.

Yongxing Wang, Xuhui Wen, Xinhua Guo[1], Feng Zhao[1], Wei Cong [7]

This paper explains the requirement of propulsion system voltage high power alternating current drives . In high power alternating current drives, the switching frequency of the devices has to be in limit in order to suppress the loss of the power semiconductor devices, torque ripple and electromagnetic interference. In this paper, a proposed drive control system with selective harmonic elimination pulse width modulation (SHEPWM) for induction motor is shown. Control is based on rotor-field oriented vector control system of induction motor with employed Pulse width modulated technique which has four different modulations. SHEPWM principle came into the existence. The results of simulations are presented over here are to verify the feasibility of control method in medium voltage high power systems (like-1.6MW). And the effectiveness of this proposed control method is verified by the experimental results in a small-scale laboratory prototype

Gianmario Pellegrino, Radu Iustin Bojoi, and Paolo Guglielmi, [8]

This paper introduces a unified direct-flux vector control scheme that is suitable for sinusoidal ac motor drives. The alternating current drives considered here are generally induction motor, synchronous reluctance, and synchronous permanent-magnet motor drives, including interior and surface-mounted Permanent magnet types. The proposed controller operates in stator flux coordinate system. The stator flux amplitude is directly controlled by the direct voltage component, while the torque is controlled by the quadrature current component. The unified direct-flux control is particularly good when flux weakening is required since it easily guarantees the production of maximum torque under current and voltage limitations. The hardware used for controlling is of standard type, and the control firmware is as well the same for all the motors which are under test with the only exception of the magnetic model used for flux estimation at slower speeds. Experimental results on various drives are given, showing the realibilty of the proposed unified control approach on laboratory prototype.

M. Nasiruddin, T. *S* . Radwan, and M. A. Rahman [9]

In this paper several aspects are considered in connecting high frequency switching converters to the grid, as for example, in all front-end rectifiers used in uninterrupted power supply, adjustable speed drives etc. High frequency switching distortions due to modulation must be taken to a lower level as much as possible from being injected into the grid and the system must be able to reject low frequency harmonic distortions from the grid or the load end. Analysis of the harmonic distortions in the LCL-filter based, three dimensional Space Vector Modulated split-capacitor rectifier was done for harmonics at both high and low -frequency levels. In both these frequency levels, the total harmonic distortion of the input current must be maintained within the given limits and also a high dynamic performance of the system is maintained. An increasing number of power grid-connected power electronic converters use an input LCL-filter in place of an L-filter.

Sibel Zorlu, Member, IEEE, 2Ibrahim Senol, Member, IEEE [10]

In this study, vector control of an alternating current brushless servomotor is performed using the current controlled, voltage source inverter and hysteresis pulse width modulated method. Using

vector control, three phase variables of the motor is transformed on the synchronously rotating d and q axis, and the control can be achieved like in the case of direct control motor. In order to get Pulse width modulated signals, an error value is calculated by comparing the current reference and actual current, and it is used as an input for hysteresis current controller. Then, the voltage vector is obtained, and the motor is driven by using the inverter so as to follow current reference values. Finally the servomotor speed is varied by using this one, and results are presented. Using this custom-designed motion control, high performance drive systems and complex algorithms can be generated. Since the proposed system is very flexible and reliable, it can be also applicable for studies on sensor less servomotor .

CHAPTER-3
INDUCTION MOTORS

3.1 INDUCTION MOTOR

An induction or asynchronous motor is a type of alternating current motor where power is supplied to the rotor by the means of electromagnetic induction, rather than commutator or slip rings as in other types of motor. These motors are generally used in industrial drives, particularly poly phase induction motors, because they are rugged and they do not have brushes. Single-phase versions are used where small applications are needed. Although most alternating current motors have long been used in fixed-speed load drives, they are also increasingly being used in variable-frequency drive (VFD) services, variable-torque centrifugal fan, pump and the compressor loads are being by far the most important energy saver type applications for variable frequency drive service. Squirrel cage induction motors are very commonly used in both fixed-speed and Variable frequency drive applications

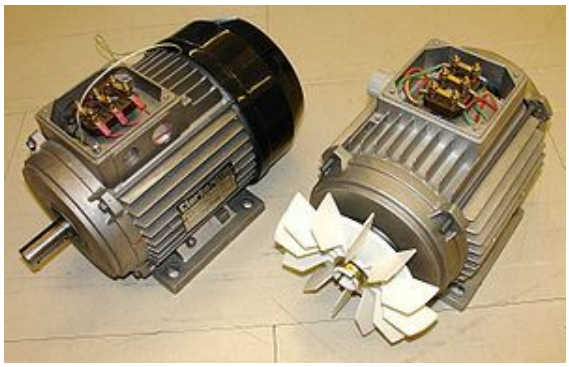

Fig.3.1 three phase induction motor [12]

Two three-phase induction motors are shown in the above figure. The motor on the right side has the end cover removed, which shows the cooling fan. In this "totally enclosed fan-cooled" type of motor, outside air cannot pass through the interior of the motor.

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3.1.1 Squirrel cage rotor

Almost eighty five percent of motors are Squirrel cage type , because this type of motor has the simplest and rugged construction and it cannot be destructed. The rotor is having cylindrical laminated core with parallel slots for carrying rotor conductors, which it should be noted that, are not wires but consists of heavy bars of copper, aluminium or various alloys . One bar is placed in each of slot, rather the bars are inserted from the end when semicircle slots are placed. The rotor bars are electrically bolted or mechanically welded to two heavy short circuiting end rings, thus giving us a Squirrel cage construction.

The rotor slots are not paralleled to the shaft, but they are purposely given a slight skew. This is very useful in two ways

1) It helps motor to run quietly by reducing the magnetic hum
2) It helps in reducing locking tendency of rotor

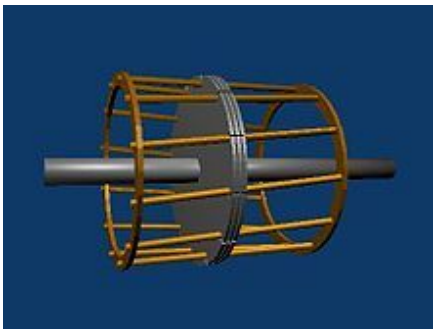

Fig 3.2 Squirrel cage rotor[12]

3.1.2 Principle of operation

In both asynchronous and synchronous motors, the alternating power supplied to the motor's stator creates a magnetic field that rotates in time with the alternating current oscillations. Whereas a synchronous motor's rotor runs at the same speed as the stator field, an induction motor's rotor rotates at a quite slow speed than the stator field. The induction motor stator's magnetic field is therefore changing or rotating This induces an opposing current in the induction

motor's rotor, in the secondary winding, when the latter is short-circuited or closed through an external impedance.

The rotating magnetic flux induces currents in the windings of the rotor; in a manner similar to the currents induced in transformer's secondary windings. These currents in turn generate magnetic fields in the rotor that are in phase opposition to the stator field. Due to Lenz's Law, the direction of the magnetic field created will be such as to oppose the change in current through the windings. The means of induced current in the rotor is the rotating stator magnetic field, so to oppose this field the rotor will start to rotate in the direction of the rotating stator magnetic field. The rotor speed accelerates until the magnitude of induced rotor current and torque maintains the applied load. Since rotation at synchronous speed would cause zero induced rotor current, an induction motor always operates slower than synchronous speed

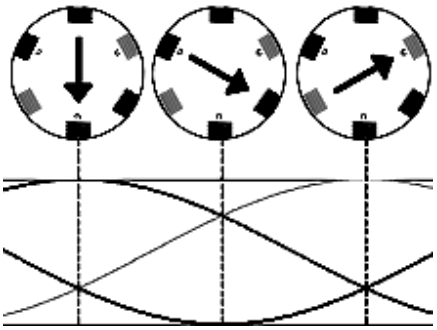

Fig.3.3 Three- phase power supply provides a rotating magnetic field in an induction motor.[18]

For these currents to get induced, the speed of the rotor must be quite slower than that of the stator's rotating magnetic field, or the magnetic field is not moving relative to the rotor conductors and no currents would be induced. As the speed of the rotor goes down the synchronous speed, the rate of rotation of the magnetic field in the rotor increases, inducing more current in the windings and generating more torque. The ratio between the rotation rate of the magnetic field as shown by the rotor (slip speed) and the rotation rate of the stator's rotating field is called "*slip*". Under various loading conditions, the speed drops and the slip increases enough to create sufficient torque to turn the load. For such reason, induction motors are

sometimes referred to as asynchronous motors. An induction motor can also be used as an induction generator, or it can be unrolled to form the linear induction motor which can generate linear motion directly.

3.2 SYNCHRONOUS SPEED

The *synchronous speed* of an alternating current motor is the rate of rotation of the rotating magnetic field created by the stator. It is always an integer fraction of the supply frequency. The synchronous speed n_s in revolutions per minute (RPM) can be given by:

$$Ns = \frac{120\ f}{p}$$

where *f* is the frequency of the alternating current supply current in Hz and *p* is the number of magnetic poles per phase. When using total number of poles, use 120 as constant instead of 60. For example, a small phase motor has six magnetic poles arranged as three opposing pairs 120° apart, each one is powered by one phase of the supply current. So there is one pair of poles per phase, which means p = 1, and for a line frequency of 50 Hertz the synchronous speed is 3000 revolutions per minute..

3.3 SLIP

The slip *s* may be defined as 'the difference between synchronous speed and operating speed, at the same frequency, expressed in rpm or in percentage or ratio of synchronous speed. Though it is expressed in so many revolutions per second, yet it is usual to express it as a percentage of synchronous speed. Actually, the term slip explains the way in which rotor slips back from synchronism.

$$\text{Slip speed} = \frac{Ns-Nr}{Ns}$$

3.3.1 Torque curve

The torque exerted by the motor as a function of slip is given by a torque curve. Over a motor's normal load range, the torque curve is close to a straight line, so the torque is proportional to the slip. As the load goes beyond the rated load, increase in slip provide less additional torque, so the

torque line begins to curve over. Finally at a slip of around twenty percent the motor reaches its maximum torque, called the "*breakdown torque*". If the load torque reaches this value, the motor will stall. At values of slip above this, the torque decreases. In three phase motors the torque goes down but still remains high at a slip of hundred percent (stationary rotor), so these motors are self-starting type. The starting torque of an induction motor is less than that of other types of motors, but still around at three hundred percent of rated torque. In two pole single-phase motors, the torque goes to zero at hundred percent slip (zero speed), so these require some changes to the stator such as shaded poles to provide starting torque.

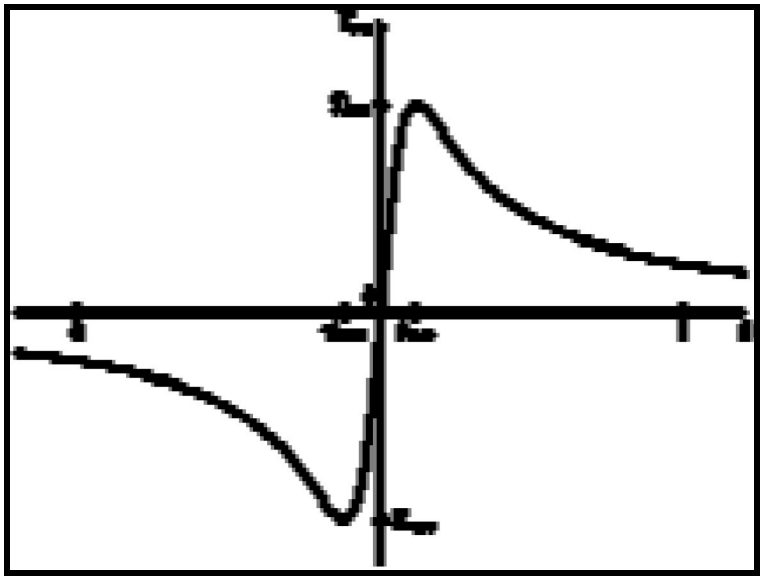

Fig.3.4 Typical torque curve as a function of slip (slip is represented by g here, which is proportional to s in the formula at left.[5]

3.4 CONSTRUCTION

The stator of an induction motor consists of poles carrying supply current to induce a magnetic field that links the rotor. To make the full use of distribution of the magnetic field , the windings are distributed in slots around the stator, with the magnetic field having the same number of north and south poles. Induction motors are commonly run on single-phase or three-phase power, but two-phase motors exist; in theory, induction motors can have any number of phases. There are generally three types of rotor: squirrel cage rotors made up of skewed or slanted (to reduce

the noise) bars of copper or aluminum that span the length of the rotor, wound the rotor with windings connected to slip rings replacing the bars of the squirrel cage, and solid core rotors are made up of mild steel..

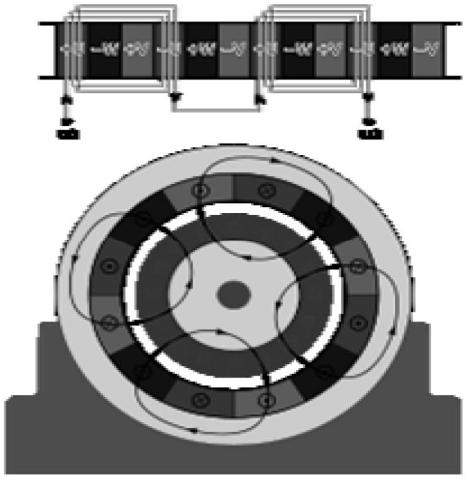

Fig.3.5 Typical winding pattern for a 3 phase, 4 pole motor [18].

3.5 SPEED CONTROL

By varying the power line frequency by making the use of an inverter, induction motors can be kept on the stable part of the torque curve above the peak value over a wide range of rotation speeds. However, the inverters can be costly, and fixed line frequencies and other start up methods are also employed instead. The theoretical unloaded speed (with slip approaching to zero) of the induction motor is controlled by the number of pair of poles and the frequency of the voltage supplied.

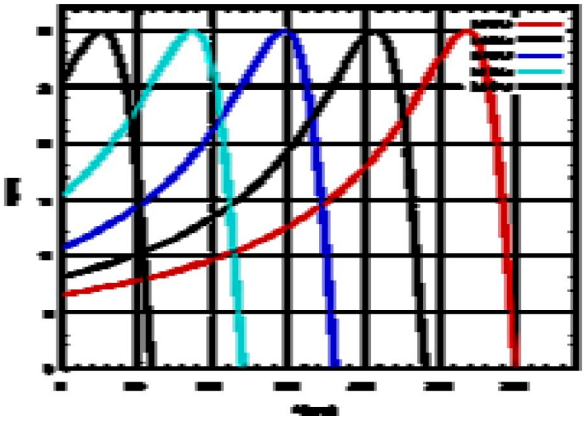

Fig.3.6 Typical torque curves for different line frequencies [6]

When motor is driven from a fixed power line frequency, loading the motor will reduce the rotation speed. When the motor is used in this manner, induction motors are usually run so that the shaft rotational speed is kept above the peak torque point; then the motor will continue to operate at constant speed. Below this point, the speed will become unstable and the motor may stall or run at reduced shaft speed, depending on the type of the mechanical load.

Before the development of power semiconductor devices, it was difficult to change the frequency, and squirrel-cage induction motors were mainly used in constant speed applications. Applications such as electrical overhead cranes used direct current drives or wound rotor motors with slip rings for rotor circuit connection to variable external resistance allowing speed control. Huge slip-ring motor drives, termed as slip energy recovery systems, among which, some are still in use, recover energy from the rotor circuit, rectify it, and then return it to the power grid using a Variable frequency drives. In many industrial adjustable-speed applications, Direct current drives are being replaced by Variable frequency drive-fed induction motors.

3.5.1 Rotation reversal

The process of changing the direction of rotation of an induction motor depends on whether it is a three-phase or single-phase machine. In the case of three phase machine, the reversal can be done by swapping the connection of any of the two out of the three power phases. In the case of a single-phase motor it is generally carried out by changing the connections of a starting

capacitor from one part of a motor winding to the another. In this case both the motor windings are in practice similar (e.g. in washing machines).

3.6 STEINMETZ EQUIVALENT CIRCUIT

Many applied motor relationships between time, current, voltage, speed, power factor and torque can be obtained by the study of the Steinmetz equivalent circuit, which is a mathematical model used to describe how an induction motor's electrical input is transformed into purposeful mechanical energy output. The equivalent circuit is a single-phase representation of a multiphase induction motor that is valid only in steady-state balanced-load conditions.

Neglecting mechanical incapabilities, the basic components of the induction motor equivalent circuit are:

- Stator resistance and leakage reactance
- Rotor resistance and leakage reactance
- Rotor slip Magnetizing reactance
- Inertia of the motor and mechanical load.

An induction motor is like an electrical transformer, the magnetic circuit of which is separated by an air gap lying between the stator winding and the moving rotor winding. The equivalent circuit can accordingly be shown either with equivalent circuit components of respective windings which are separated by an ideal transformer or with rotor components which are referred to the stator side as shown in the following equivalent circuit .

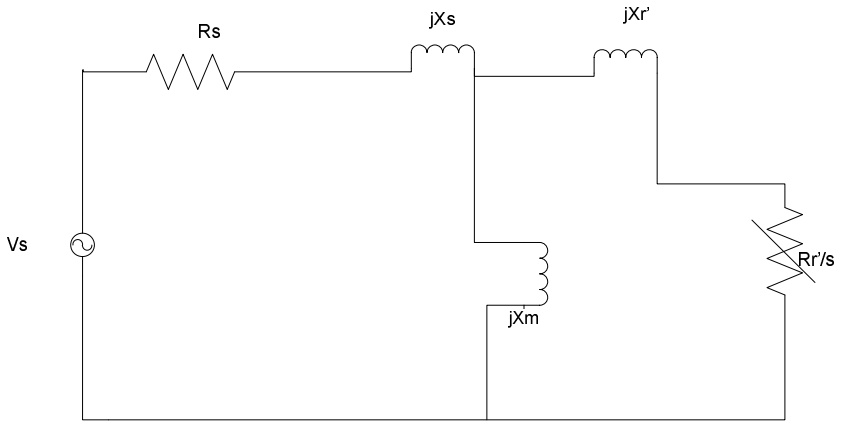

Fig.3.7 Equivalent circuit of Induction motor

3.6.1 Power factor

The power factor of induction motors can be changed with that of the load, from around 0.85 or 0.9 at full load to as low as 0.35 at no-load, because of stator, rotor leakage reactance and magnetizing reactance Power factor can be improved by connecting various capacitors (either in star or delta) either on an individual motor or, it can be connected on a common bus covering several motors. For economic and various other types of considerations, power systems are very rarely corrected by power factor, or higher than, unity power factor. Power capacitors applications with harmonic currents and voltages requires power system study to avoid resonance between capacitors, transformer and various types of circuit reactances. Common bus power factor correction is allowed to minimize the resonance risk and to simplify power system study.

3.7 STARTING

A single phase induction motor is not at all self-starting; thus, it is mandatory to provide a starting circuit and associated start windings to give the initial starting in a single phase induction motors. The normal windings within such a motor can cause the rotor to turn in either direction, so the starting circuit is responsible for determining the operating direction well.

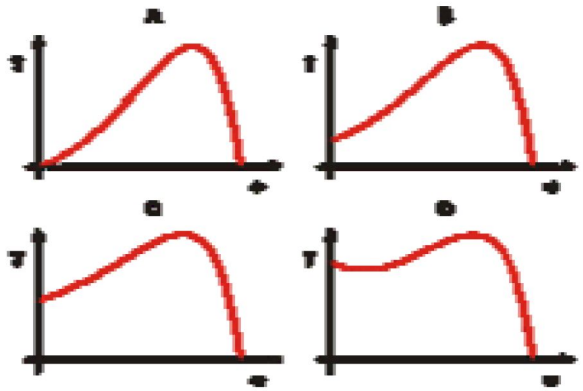

Fig.3.8 Torque curves for 4 types of asynchronous induction motors [3]

A multi phase induction motor is self-starting and produces torque even at standstill. Available squirrel cage induction motor starting methods includes the direct on-line starting, star-delta

CHAPTER-4

TOTAL HARMONIC DISTORTION

4.1 INTRODUCTION

The total harmonic distortion, or THD, of a signal is a measurement of the harmonic distortion present and is defined as the ratio of the sum of the powers of all harmonic components to the power of the fundamental frequency. THD is used to get the linearity of audio systems and the power quality of electrical power systems.

In audio systems, lower THD means the components in a loudspeaker, amplifier or microphone or other equipment produce a more accurate reproduction by reducing harmonics added by electronics and audio media.

In power systems, lower THD means reduction in peak currents, heating, emissions, and core loss in motors.

4.2 CONCEPT OF HARMONICS

To understand a system with an input and an output, such as an audio amplifier, we start with an ideal system where the transfer function is linear and time-invariant. When a signal passes through a non-ideal, non-linear device, additional distortion content is added at the harmonics of the original frequencies. THD is a measurement of the extent of that distortion.

When the input is a pure sinusoidal waveform, the measurement is most commonly the ratio of the sum of the powers of all higher harmonic frequencies to the power at the first harmonic, or fundamental frequency:

$$\text{THD} = \frac{\sqrt{I2^2 \quad I^2 \quad \cdots\ldots\ldots\ldots\ldots In^2}}{I^2}$$

Measurements based on amplitudes (e.g. voltage or current) must be converted to powers to make addition of harmonics distortion understandable. For a voltage waveform, for example, the ratio of the squares of the root mean square voltages is equivalent to the power ratio:

$$\frac{\sqrt{V2^2 \quad V^2 \quad \cdots\ldots\ldots\ldots..V\infty^2}}{VI^2}$$

where V_i is the RMS voltage of ith harmonic and $i = 1$ is the fundamental frequency.
THD is also commonly defined as an amplitude ratio rather than a power ratio, resulting in a definition of THD which is the square root of that given above:

$$\frac{\sqrt{V2^2 \quad V^2 \quad V^2 \ldots\ldots\ldots\ldots\ldots\ldots.V\infty^2}}{V^2}$$

This latter definition is commonly used in audio distortion (percentage THD) specifications. It is unfortunate that these two conflicting definitions of THD (one as a power ratio and the other as an amplitude ratio) are both in common value in daily life.

As a result, THD is a non-standardized specification and the results between manufacturers can not be easily compared. Since individual harmonic amplitudes are measured, it is required that the manufacturer disclose the test signal frequency range, level and gain conditions, and number of measurements taken. It is possible to measure the full 20–20 kHz range using a sweep. For all signal processing equipments, except microphone preamplifiers, the preferred gain setting is unity. For microphone preamplifiers, standard value is the maximum gain.

Measurements for calculating the THD are made at the output of a device under specified conditions. The THD is usually expressed in percentage as distortion factor or in decibels relative to the fundamental as distortion attenuation.

4.3 THD PLUS NOISE

THD+N means total harmonic distortion plus noise. This measurement is much more common and more comparable between various devices. It is generally measured by inputting a sine waveform, notch filtering the output, and comparing the ratio between the output wave with and without the sine wave.
A meaningful measurement must include the bandwidth of the measurement. This measurement includes effects from inter modulation distortion, and so on, in addition to harmonic distortion.

In Europe, it is preferable to apply an ITU-R BS.468 weighed curve which is intended to accentuate what is most audible to the human ear, contributing to a more accurate measurement. However, as the weight of the curve sums up 12 dB of gain to the critical mid band making THD+N measurements bigger, manufacturers object to its use and have widely prevented its adoption in American and Asian markets.

For a given input frequency and amplitude, THD+N is equal to SINAD, provided that both measurements are made over the same bandwidth.

4.4 MEASUREMENT

The distortion of a waveform relative to a pure sine wave can be measured either by using a THD analyzer to analyse the output wave into its constituent harmonics and taking the amplitude of each relative to the fundamental; or by cancelling out the fundamental with a notch filter and measuring the remaining signal, which will be total aggregate harmonic distortion plus noise.

Given a sine wave generator of very low inherent distortion, it can be used as input to amplification equipment, whose distortion at different frequencies and signal levels can be measured by examining the output waveform.

There is an electronic equipment both to generate sine waves and to measure distortion; but a general-purpose digital computer equipped with a sound card can carry out harmonic analysis with given software. Different software can be used to obtain sine waves, but the inherent distortion may be too high for measurement of very low-distortion amplifiers.

4.5 INTERPRETATION

For many purposes different types of harmonics are not equal. For instance, crossover distortion at a given THD is much more audible than clipping distortion at the same THD, since the harmonics produced are at higher frequencies. A single THD number is not adequate to specify the audibility, and must be interpreted with care. Taking THD measurements at different output ranges would expose whether the distortion is clipping (which generally increases with level) or crossover (which decreases with the level).

THD is an average of a number of harmonics equally weighted, even though research performed decades ago identifies that lower order harmonics are more harder to hear at the same level, compared to that with higher order ones. In addition, even order harmonics are said to be generally harder to hear than odd order harmonics. A number of formulas that attempt to correlate THD with actual audibility have been generated, however none have gained mainstream use.

- SUMMARY

  This chapter explains the concept of Total Harmonic distortion on current and voltage.

CHAPTER-5

PULSE WIDTH MODULATION

5.1 PULSE WIDTH MODULATION

Pulse-width modulation (PWM), as it applies to motor control, is a method of delivering energy through a succession of pulses rather than a continuously varying (analog) signal. By increasing or decreasing the pulse width, the controller regulates energy flow to the motor shaft. The motor's own inductance acts like a filter, it stores energy during the "on" cycle while releasing it at a rate corresponding to the input or reference signal. In other words, we can also say that energy flows to the load not so much the switching frequency, but at the reference frequency.

. The mean value of voltage (and current) fed to the load is controlled by turning the switch between supply and load on and off at a fast speed. If the the switch is on for the longer time compared to the off periods, the higher the switching on period.

The PWM switching frequency has to be much faster than that would affect the load, which is said that the device uses the power. Typically switching have to be done various times a minute in an electric stove, 120 Hz in a lamp dimmer, from few kilohertz (kHz) to tens of kHz for a motor drive and well into the tens or hundreds of kHz in audio amplifiers and computer power supplies.

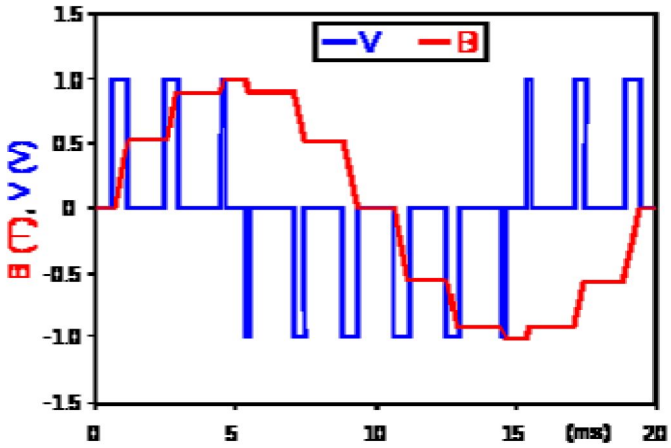

Fig.5.1 An example of PWM in an AC motor drive [3]

The phase-to-phase voltage (rectangle) shown is modulated as a series of pulses that results in a sinewave-like flux density waveform (sine wave) in the magnetic circuit of the motor. The smoothness of the resultant waveform can be controlled by the width and number of modulated impulses (per given cycle)

Pulse-width modulation (PWM), or pulse-duration modulation (PDM), is a general technique used for controlling power to inertial electrical devices, made practical by modern electronic power electronics switches.

The term *duty cycle* describes the proportion of 'on' time to the regular interval or 'period' of time; a low duty cycle corresponds to low power, because the power is off for most of the time. Duty cycle is expressed in percent, 100% being fully on.

The main advantage of PWM is that power loss in the switching devices is very less. When a switch is off there is practically no current, and when it is on, there is almost no voltage drop across the switch. Power loss, as being the product of voltage and current, is thus in both cases is close to zero. Pulse width modulation also works in a good manner with digital controls, which, because of their on/off nature, can easily set the needed duty cycle. Pulse width modulation has also been used in certain communication systems where its duty cycle has been used to send information over a communications channel

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5.2 PRINCIPLE

Pulse-width modulation generally uses a rectangular pulse wave whose pulse width is modulated which results in the variation of the average value of the waveform. Suppose we consider a pulse waveform F(t) with a low value Ymin, a high value Ymax and a duty cycle σ, the average value of the waveform is shown figure 5.2.

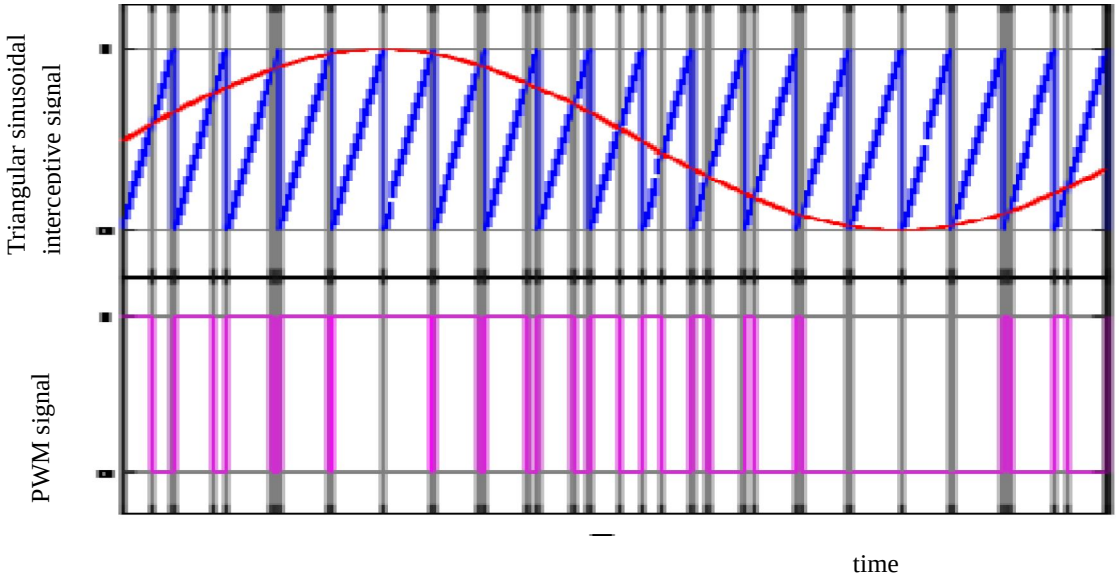

Fig.5.2 A simple method to generate the PWM pulse train corresponding to a given signal is the inter-sective PWM [3]

The signal (here we are considering the sine wave) is compared with a saw tooth waveform (or triangular waveform) (blue). When the latter is less than the former, the PWM signal (magenta) is in up state (1). Otherwise it is in the low state (0).

The simplest way to generate a PWM signal is the intersecting method, which requires only a saw tooth or a triangle waveform (it can be easily generated using a simple oscillator) and a comparator. When the value of the reference signal (the red sine wave in figure 5.2) is more than the modulation waveform (blue), the Pulse width modulated signal (magenta) is in the high state, otherwise it is in the low state.

5.2.1 Delta modulation

In the use of delta modulation for Pulse width modulation control, the output signal is integrated (or it is summed up), and the result is compared with limits, which correspond to a Reference signal specified by a constant. Every time the integral of the output signal reaches one of the limits, the Pulse width modulated signal changes state.

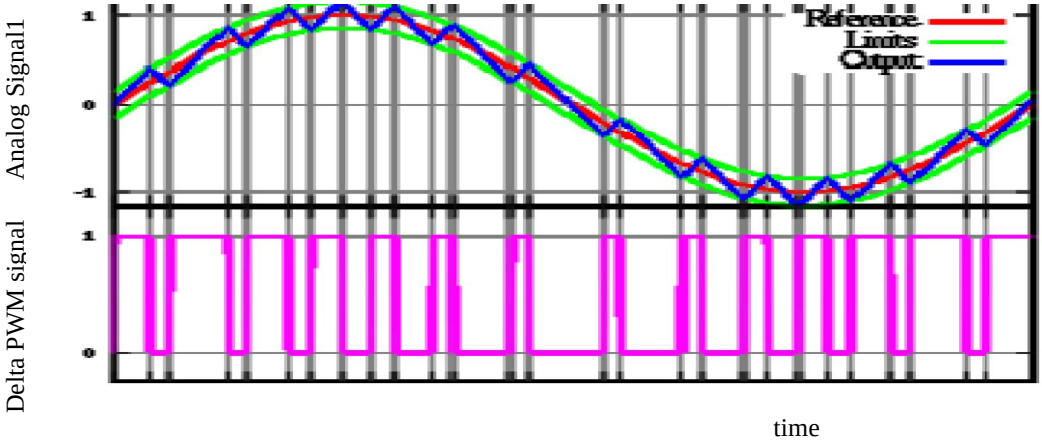

Fig. 5.3 Principle of the delta PWM.[3]

The output signal (which is shown by the blue colour) is compared with the limits. These limits correspond to the reference signal (the red one), offset by a given value. Every time the output signal 78899 reaches one of the limits, the Pulse width modulated signal changes state.

5.2.2 Delta-Sigma Modulation

In delta-sigma modulation as a Pulse width modulation control system, the output signal is subtracted from a reference signal to form an error signal. This error is integrated, and when the integral of the error exceeds the limits, the output changes state itself(either it goes high or it goes low).

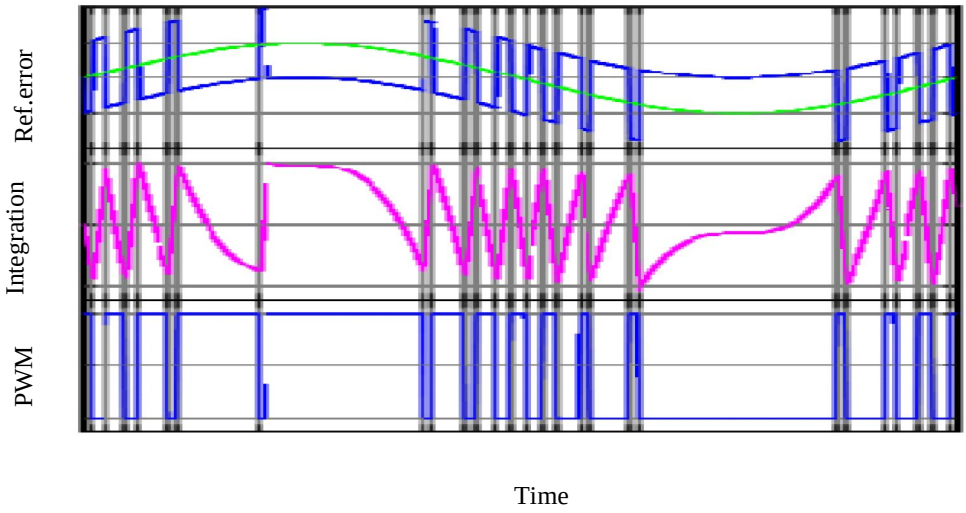

Fig. 5.4 *Principle of the sigma-delta PWM.[4]*

The top green waveform is the reference signal, on which the output signal (Pulse width modulated, in the bottom plot) is subtracted to form the error signal (blue waveform, in the top plot). This error is integrated (shown in the middle plot), and when the integral of the error exceeds the limits (shown by red lines), the output changes state.

5.2.3 Space Vector Modulation

Space vector modulation is a Pulse width modulation control algorithm for multi-phase AC generations, in which the reference signal is sampled regularly; after each sample, non-zero active switching vectors which are adjacent to the reference vector and one or more of the zero switching vectors are taken for the appropriate fraction of the sampling period in order to get the reference signal as the average of the used vectors.

5.2.4 Direct torque control (DTC)

Direct torque control is a method which is used to control the alternating current motors. It is closely related to the delta modulation (please see above). Motor torque and magnetic flux are calculated and these are controlled to stay within their hysteresis band limits by turning on new combination of the device's semiconductor switches each time even if the signal tries to deviate out of the band.

5.3 TIME PROPORTIONING

Many digital circuits can generate Pulse width modulated signals (e.g., many microcontrollers have Pulse width modulated outputs). They normally use a counter that increases periodically (it is connected directly or indirectly to the clock of the circuit) and it is reset at the end of every period of the PWM. When the counter value is quite more than the reference value, the PWM output changes state from more to less (or low to high). This method is referred to as time proportioning, particularly it is referred as time-proportioning control – in which *proportion* of a fixed cycle time is spent in the high state.

The increased and periodically reset counter is the discrete state of the intersecting method's that is saw tooth wave. The analog comparator of the intersecting method will become a simple integer comparison between the current counter value and the digital (possibly digitized) reference value. The duty cycle can only be changed in discrete steps, as the function of the counter resolution. However, a high-resolution counter can provide quite good performance.

5.4 PWM SAMPLING THEOREM

The process of pulse width modulation conversion is a non-linear and it is also supposed that low pass filter signal recovery is imperfect for PWM. The Pulse width modulated sampling theorem states that PWM conversion can be perfect upto a limit. The theorem states that "Any band limited baseband signal within the range (±0.637) can be represented by a pulse width modulation (PWM) waveform with unit amplitude. The number of pulses in the waveform is equal to the number of Nyquist samples and the main constraint is independent of whether the waveform is a two-level or three-level."

5.5 SINUSOIDAL PULSE WIDTH MODULATION

SPWM (Sinusoidal pulse width modulation) signals are used in micro-inverter design (used in solar or wind power generations). This switching signals are fed to the Field effect transistors that are used in the device and its efficiency depends upon the harmonic content of the generated Pulse width modulated signal. There is a lot of work done to eliminate unwanted harmonics and improve the fundamental strength, some of which involve the usage of a modified carrier signal

instead of a classic saw tooth waveform in order to decrease power losses and improve the efficiency. Another common application is in robotics i.e., Pulse width modulated signals are used to control the speed of the robot by controlling the motors.

- **SUMMARY I**n this chapter, the concept of Pulse width modulation is realized and it is also explained that how it is used for switching purposes.

CHAPTER-6
VECTOR CONTROL

6.1 VECTOR CONTROL (FOC)

Vector control, it is also called field-oriented control (FOC),it is basically a variable frequency drive (VFD) control method which controls three-phase alternating current electric motor output by means of three controllable VFD inverter output variables:

- Voltage magnitude
- Voltage angle
- Frequency.

Field oriented control is a technique used in AC synchronous and induction motor applications that was originally generated for high-performance motor applications which can operate smoothly over the full speed range, and can also generate full torque at zero speed, and it is capable of fast acceleration and deceleration but that is becoming very attractive for lower performance applications as well due to FOC's motor size, cost and consumption of power and its reduction superiority over other methods. Not only is FOC very common in induction motor control methods due to its conventional superiority in high-performance applications, but the expectation is that it will also nearly universally displace single-variable scalar volts-per-Hertz (V/f) control.

The Park transformation has long been widely used in the analysis and performance of synchronous and induction machines. The transformation is by far the single most important concept needed for an understanding of how Field oriented control works, the concept having been first came into existence in a 1929 paper authored by Robert H. Park. Park's paper was the second most important in terms of impact from among all power engineering related papers were published in the twentieth century. The newer method of Park's work involves his ability to transform any related machine's linear differential equation set from one with that of time

varying coefficients to another with time invariant coefficients.

In direct current motor the torque is directly proportional to the armature current, but in Induction motors, the dynamic response is achieved by taking into considerations the angle between the armature magneto motive force and the stator mmf which remained at 90 degree for producing the optimal torque. Thus, in vector control of induction motor, the stator current space vector I_s is divided to two *d* and *q* rotating axis. Hence, the stator phase currents are controlled in such a manner that i_{qs} delivers the requred torque while ids is responsible for maintaining the rotor flux density at the rated value. The Iqs which is known as torque producing component and the Ids which is known as flux producing component have only direct current components in steady state condition. Thus, they are perfect to be used as control variables. Furthermore, the rotor flux linkage is moving at a speed which is equal to the synchronous speed. Therefore, the speed error obtained from the difference between the reference speed ω_r and the actual rotor speed ω, is used to get the reference torque The I_{qs} and the I_{ds} are expressed as below The main methodoloy in both direct vector control and the indirect vector control is same. In direct vector control the angular position (phase) of the vector of rotor flux in the stator reference frame (θ_r) can be measured directly.

In vector control, an alternating current induction or synchronous motor is controlled under all operating conditions like a separately excited DC motor. That is, the AC motor acts as a DC motor in which the field flux linkage and armature flux linkage created by the stator field and armature (or torque component) currents which are orthogonally aligned such that, when torque is controlled, the field flux linkage is not affected, hence getting dynamic torque response.

Vector control accordingly generates a three-phase pulse width modulation motor voltage output derived from a complex voltage vector to control a complex current vector derived from motor's three-phase motor stator current input through rotations back and forth between the three-phase speed and time dependent system coordinate system can be imposed on the motor's instantaneous (a, b, c) three-phase sinusoidal system as shown in accompanying image (phases a & b not shown for clarity). Components of the (d, q) system current vector, allow the traditional control such as proportional and integral, or PI control, as in the case of a DC motor.

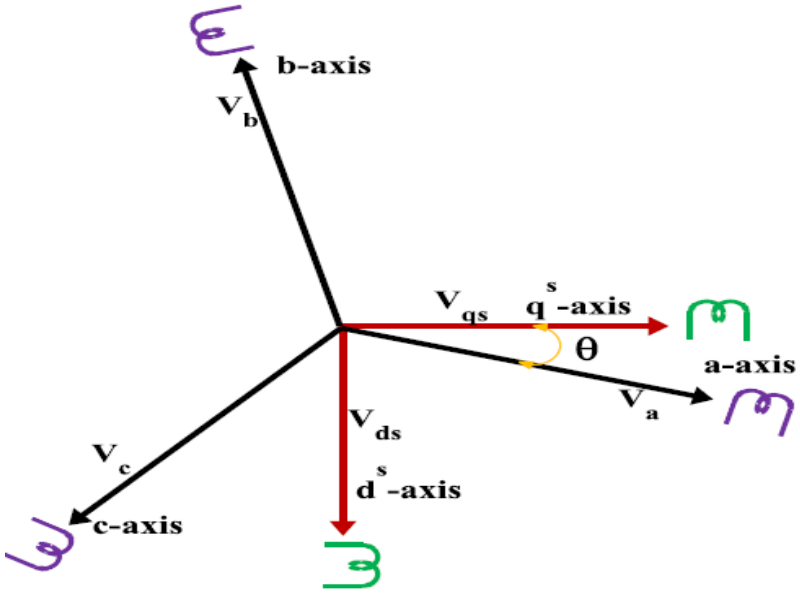

Fig 6.1 phasor representing three phase voltages and dq component of voltage phasor

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \cos\theta & \sin\theta & 1 \\ \cos(\theta - 120^0) & \sin(\theta - 120^0) & 1 \\ \cos(\theta + 120^0) & \cos(\theta + 120^0) & 1 \end{bmatrix}\begin{bmatrix} V_{qs}^s \\ V_{ds}^s \\ V_{0s}^s \end{bmatrix}$$

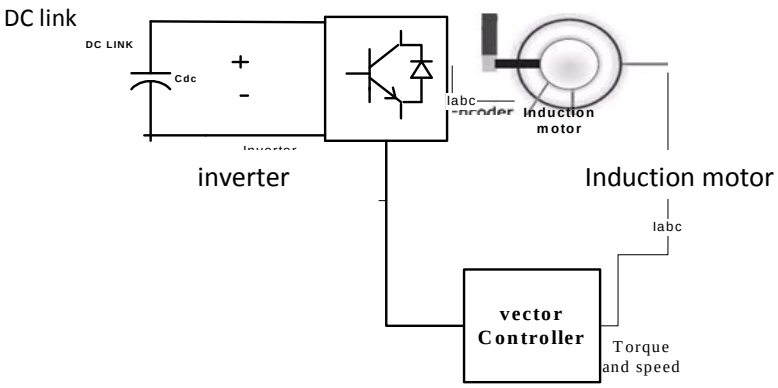

Fig. 6.2 Six Pulse fed vector controlled Induction motor drive

The rapid growth of power electronics controllers in past few years years has attracted the attention of researcher scholars for making use of flexible characteristics of an induction motor in variable frequency drives. For this purpose, the vector control of induction motor drives has been used in high performance control systems like fans in heating, ventilating, and air conditioning (High voltage alternating current) systems, blowers, rolling mills, pumps for waste water treatment plants, etc. The Vector controlled Induction motor drive employ a 6-pulse diode bridge rectifier, (for rectifying the input ac voltage) which results in injection of current harmonics in the ac mains. These current harmonics while propagating through the finite source impedance leads to the voltage distortion at the point of common coupling, thereby affecting the consumers. The widespread use of variable frequency drives has drawn attention on harmonics distortion generated by them..

A more reliable control method consists first in estimating the machine stator flux and electric torque in the stationary reference frame from terminal measurements.

The estimated stator flux and electric torque both are then controlled directly by comparing them with their respective demanded values using hysteresis band comparators. The outputs of the two comparators are then used as input signals of an switching table.

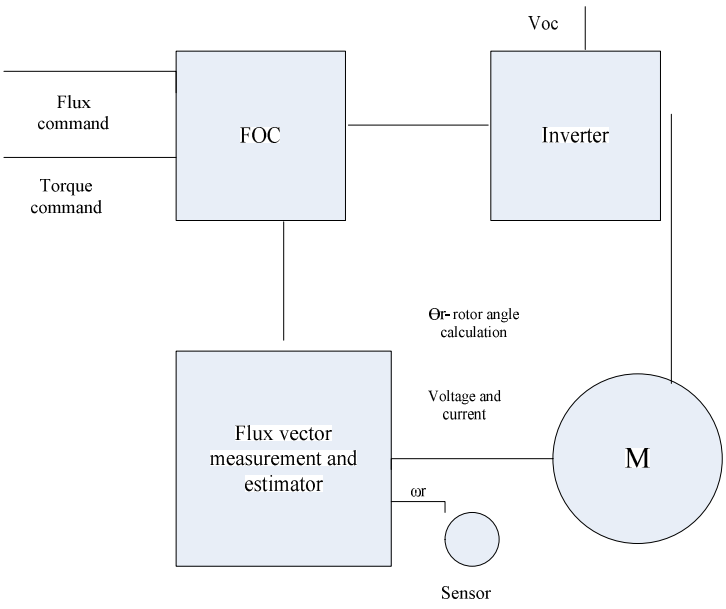

Fig.6.3*Simplified Direct FOC Block Diagram [3]*

CHAPTER-7

SIMULATION AND RESULT

7.1 SIMULATION MODEL OF PWM FED INDUCTION MOTOR DRIVE

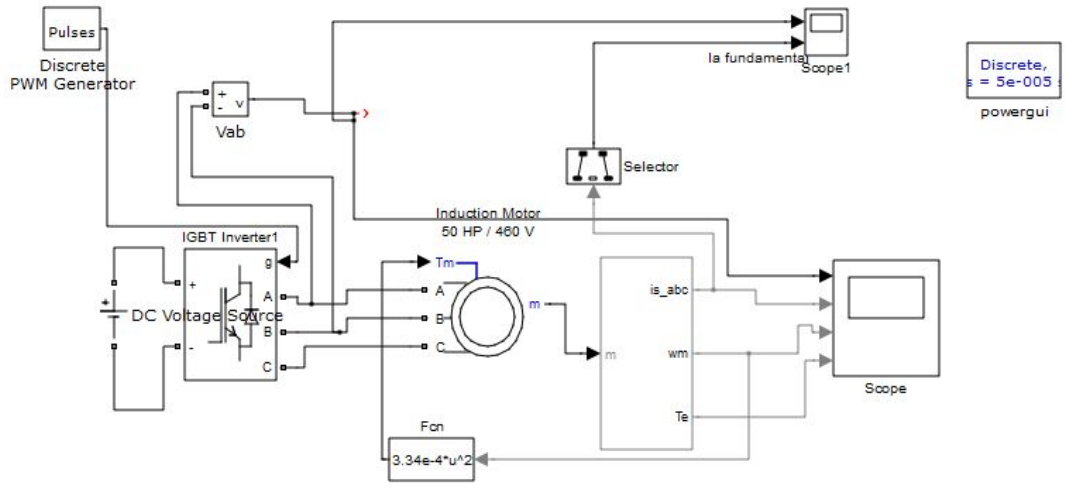

Fig7.1. Simulation diagram for PWM inverter fed induction motor

Variable speed control of alternating current electrical machines makes use of forced-commutated electronic switches such as Insulated gate bipolar transistors, metal oxide semiconductors field effect transistos, and GTOs. Asynchronous machines fed by pulse width modulation voltage sourced converters (VSC) are now gradually replacing the Direct current motors and thyristor bridges. With Pulse width modulation combined with modern control techniques such as field-oriented control(vector control) or direct torque control, you can obtain the same flexibility in speed and torque control as in the case of DC machines. This section shows how to build a simple close loop AC drive required for controlling an asynchronous machine.PWM generator is used for switching on and off purposes of IGBT inverter, a controlled ac is given to the induction motor ,a demultiplexer is used for the measurement of three phase stator currents, speed and electromagnetic torque. Waveforms can be seen by the use

of a scope. As we know that the speed is inversely proportional to torque, so by maintaining the machines speed and feed backing it to the motor can maintain the desired torque for the operation of machine.

7.1.1The waveforms of stator voltage, current , electromagnetic torque for PWM fed Induction motor drive

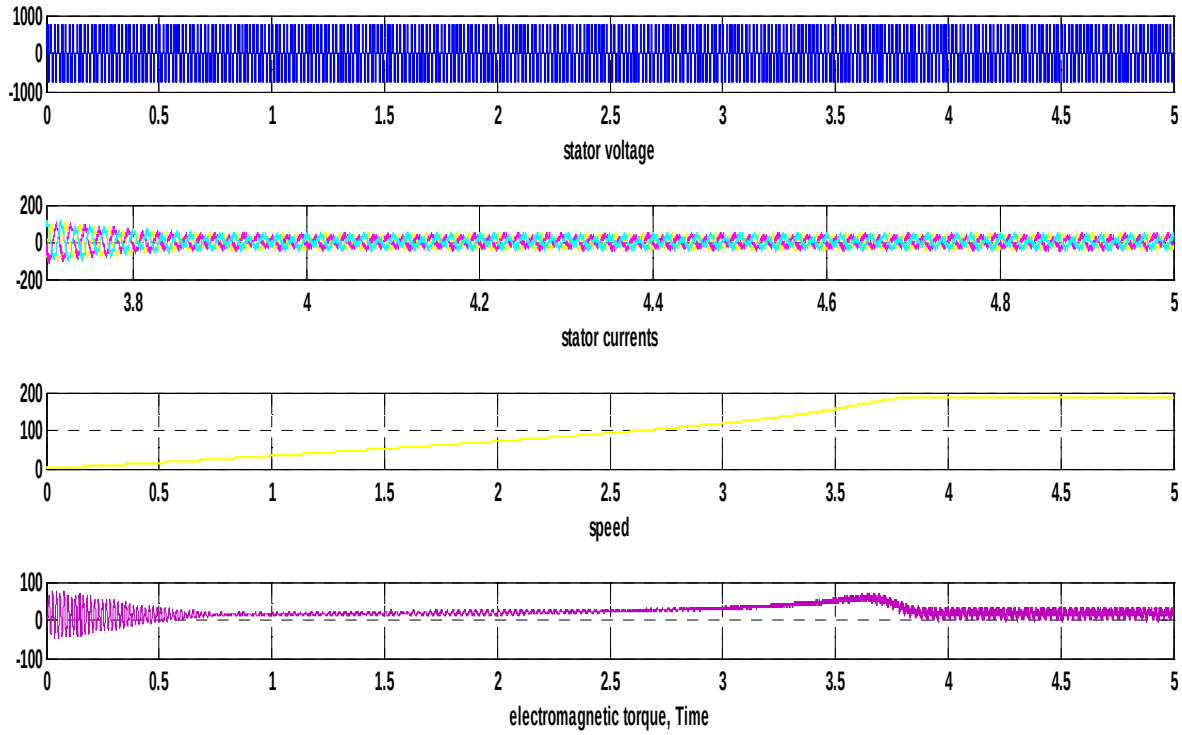

Fig7.2 The result of the stator current waveform , Electromagnetic torque and rotor speed is obtained from using PWM generation of carrier wave for Squirrel cage Induction

7.1.2 Calculation of Total Harmonic Distortion for stator current for phase a,b,c

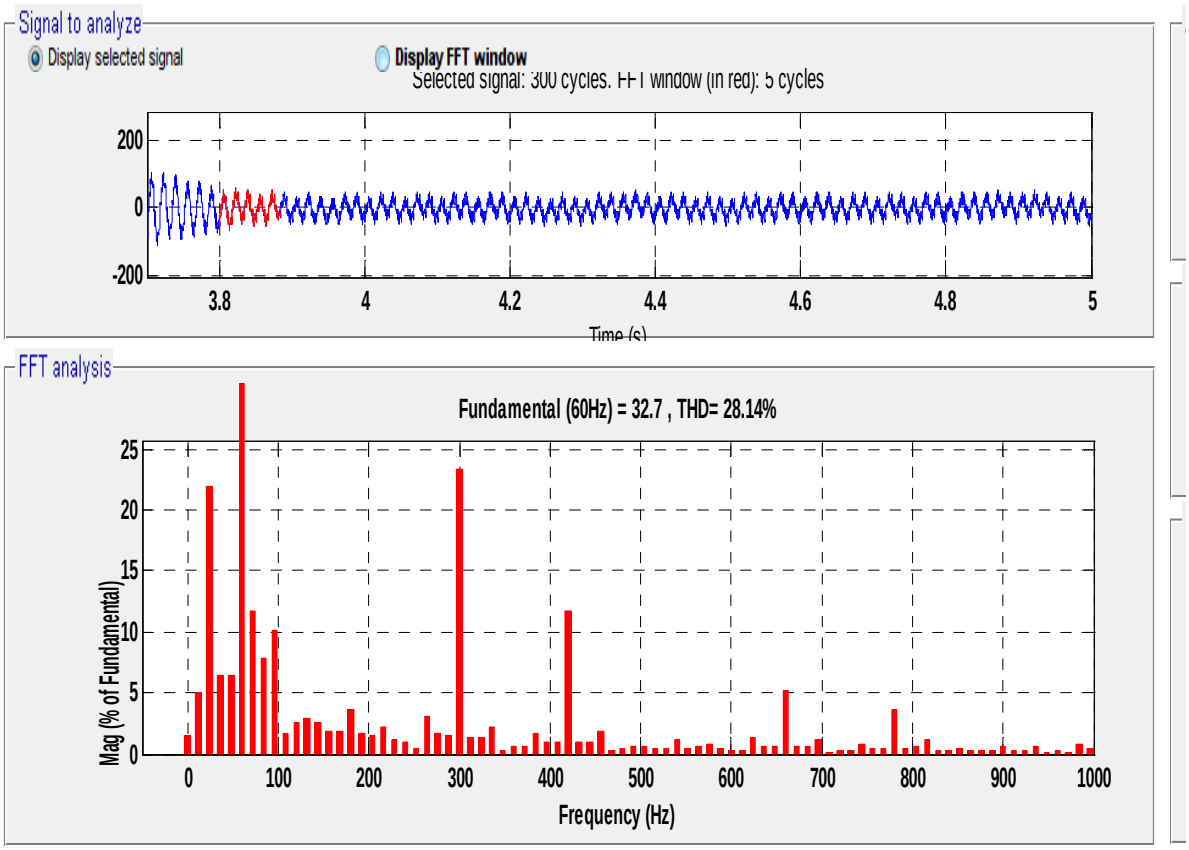

Fig.7.2 Fast Fourier transform of current waveform

THD= 28.14

7.2 SIMULATION MODEL OF VECTOR CONTROLLED INDUCTION MOTOR DRIVE

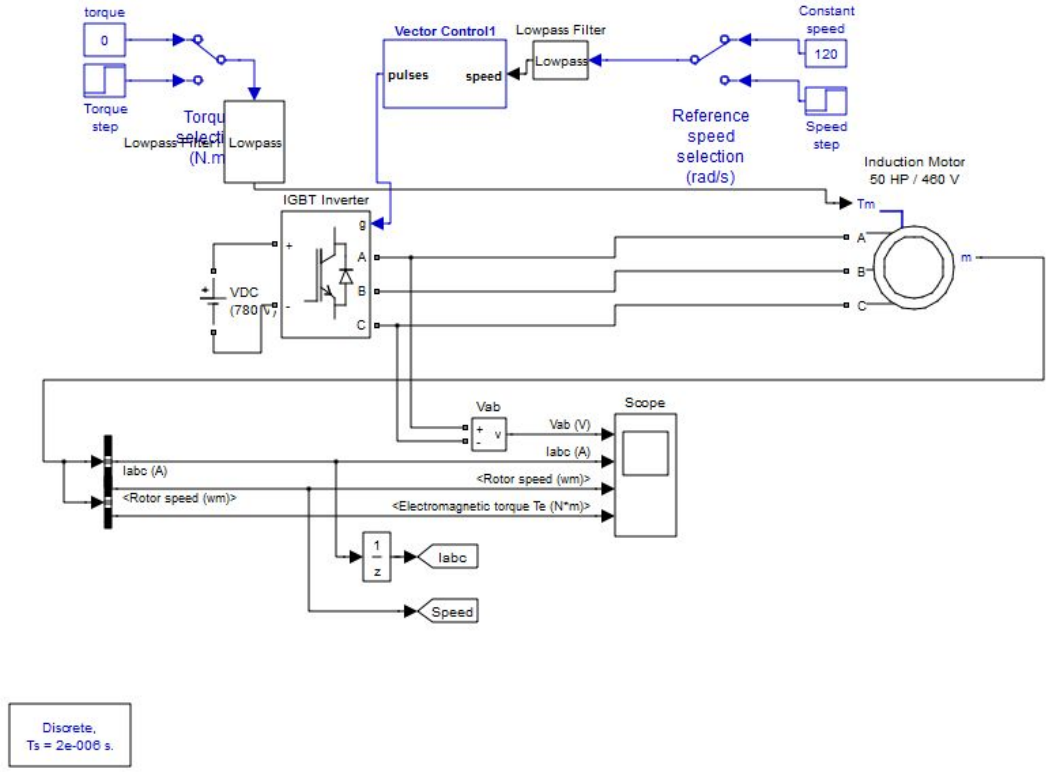

Fig.7.4 Simulation diagram for vector controlled induction motor drive

Start the simulation. Observe the motor current, voltage, and speed during the starting on the scope. At the end of the simulation time (i.e at three seconds), the system can reached its steady-state.

Response to a change in reference speed and load torque

The initial conditions state vector "Initial" will start with wm = 120 radian/s and Tl = 0 Nm is automatically loaded in workspace when we start the simulation .

7.2.1 The waveforms of stator voltage ,currents speed and electromagnetic torque

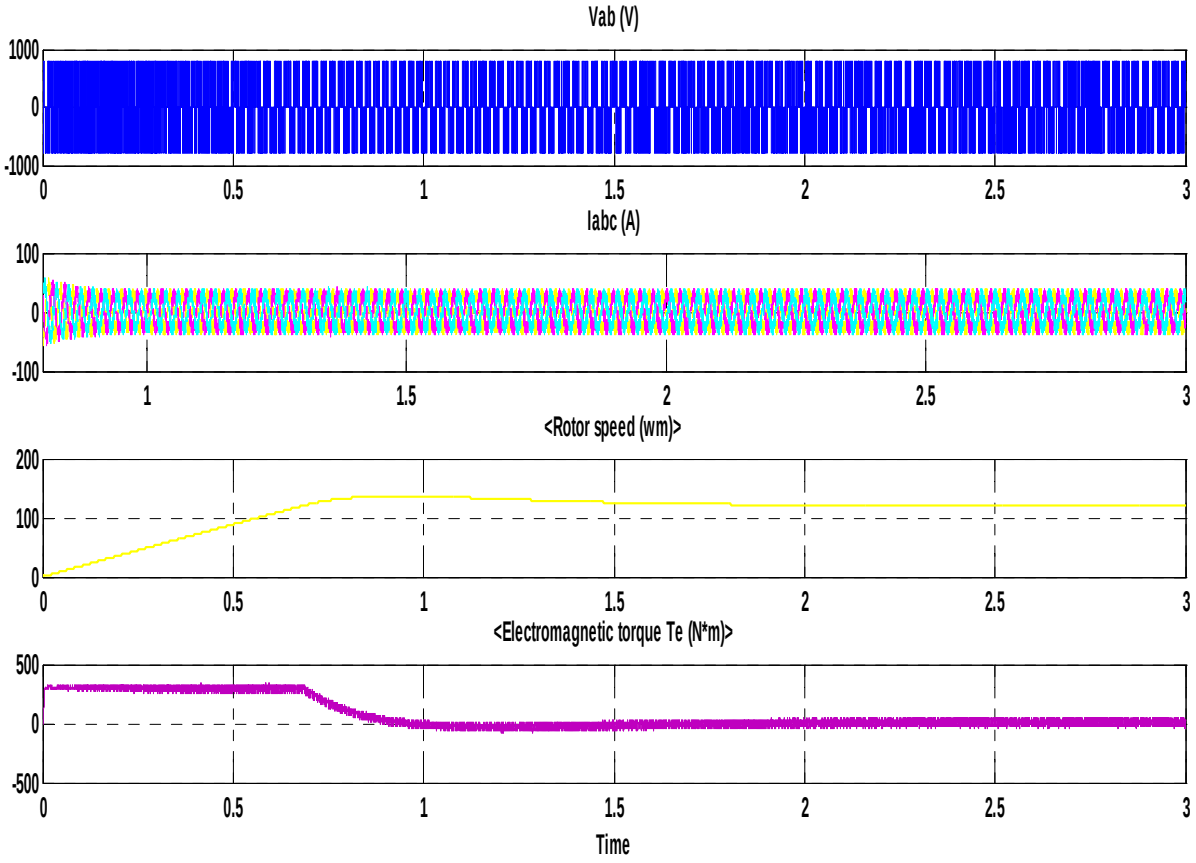

Fig. 7.5 These are the waveforms of Voltage, stator current , rotor speed and Electromagnetic torque obtained by using vector control induction motor drive at initial state

7.3 Vector Control block

Now, we can explain each and every block used in this diagram. The reference speed is compared with the motor actual speed to get the desired torque , by making the use of Proportional Integral controller and then this torque ,we can get the iqs reference component of stator current , now theta is calculated , then abc stator currents are converted from rotating reference frame to d-q stator currents, again these d-q stator currents are converted to abc reference stator currents in stationery frame. The actual stator currents a,b,c are compared with reference stator currents in a current regulator. After comparing these two currents , pulses are generated ,which are fed to the induction motors.

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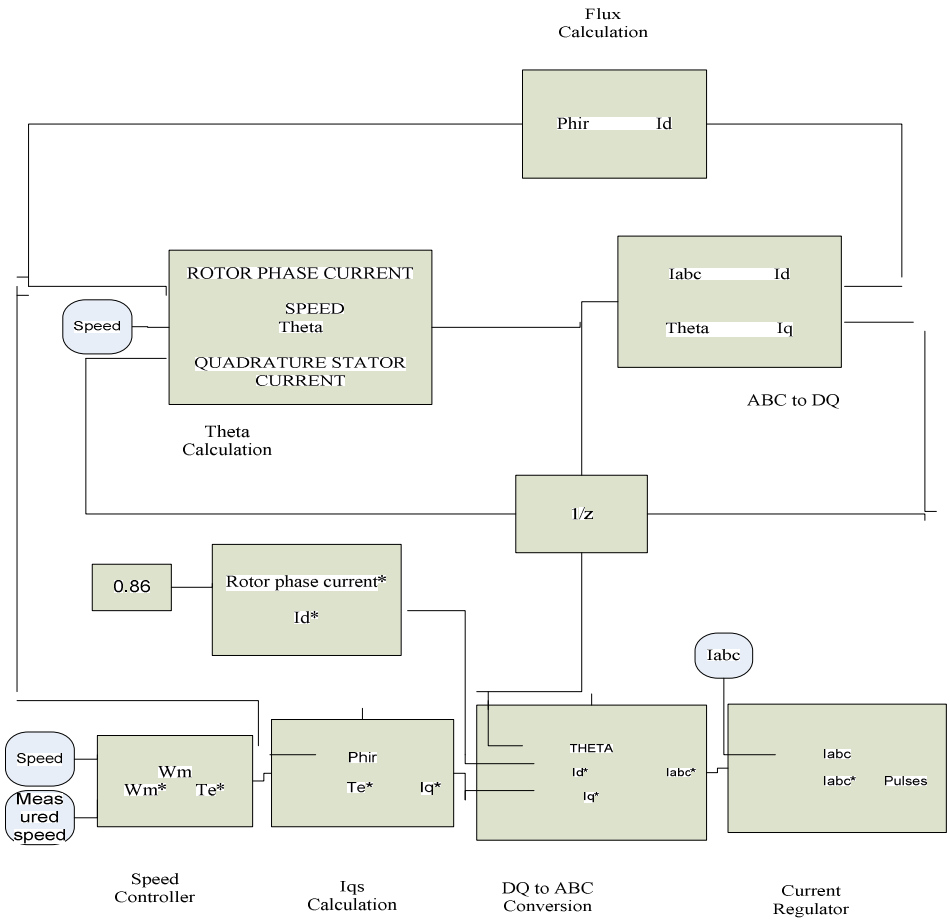

Fig.7.6 Block diagram of vector control fed to the Induction motor drive

7.3.1 Current regulator

In this diagram, logical operators are there ,then relays, which are directly or indirectly connected to produce the desired pulses.

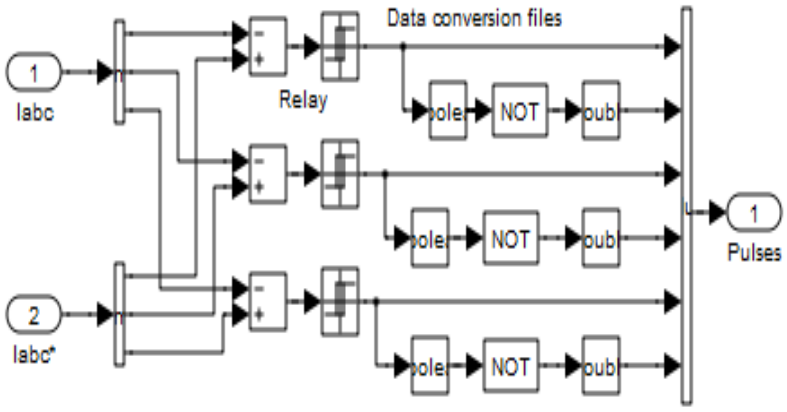

Fig.7.7 Current Regulator

Conventional two-level hysteresis band current controller operates by comparing a current error (i.e. the difference between measured and reference phase currents) against a fixed hysteresis band. When the error goes below the lower hysteresis limit, the inverter phase leg output is said to be switched high, and when the error rises above the upper hysteresis limit, the inverter output switches goes low

7.3.2 Proportional Integral Controller

Two inputs viz, actual rotor speed and reference speed are compared in this block , then the error is integrated to get the desired torque.

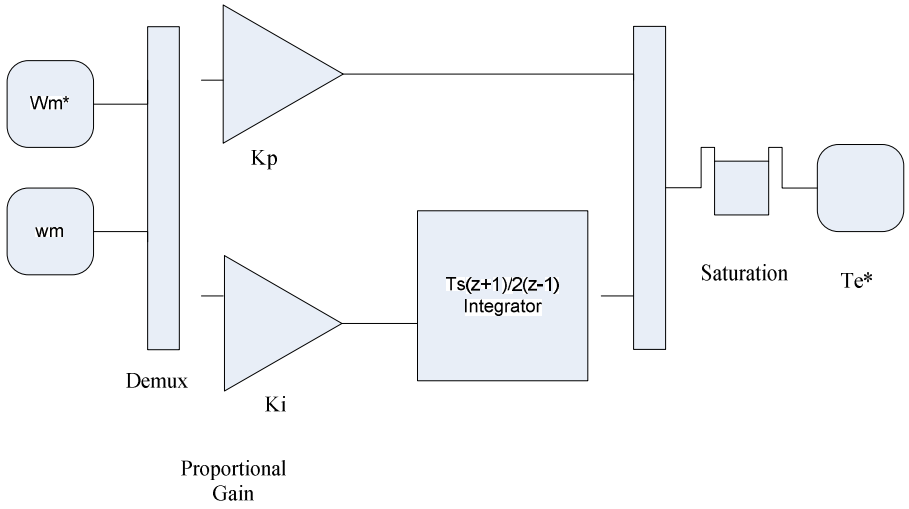

Fig.7.8 PI Controller

In the rotor-flux-oriented reference frame the d-component of the stator current reference vector i_{sd}* can be obtained as

$i_{sd}^* = i_{mr} + \tau_r(\Delta i_{mr}/\Delta T)$.

Where $\tau_r = L_r / R_r$ L_r=Rotor inductance , R_r= Rotor inductance

The closed loop Proportional integral speed controller compares the reference speed (ωr^*) with motor speed (ωr) and generates reference torque T^* (after limiting it to a acceptable value) as

$T(n)^* = T^*(n-1) + K_p \{\omega(n) - \omega(n-1)\} + K_i \omega(n)$

where $T(n)^*$ and $T(n-1)^*$ are the output of the Proportional integral controller (after limiting it to a acceptable value) and $\omega e(n)$ and $\omega e(n-1)$ refer to speed error at the nth and $(n-1)$th instants. K_p and K_i are the proportional and integral gain constants. The q-component of the stator current reference vector i_{sq}^* can be obtained from the output of the Proportional integral controller as

$i_{sq}^* = T^*/(k\, i_{mr})$

The d-component i_{sd}^* and q-component i_{sq}^* of the stator current form the inverter current reference vector in rotor-flux-oriented reference frame, is then converted to stationary reference frame using rotor flux angle which is calculated as the sum of the rotor angle and the value of slip angle as

$k = (3/2)\,(P/2)\{Lm/(1 + \sigma)\}$

i_{mr} is the magnetizing current, ω_s is the slip speed of rotor, ω is the angular velocity of rotor, P, Lm, and σ are the number of poles, mutual inductance, and rotor leakage factor, respectively, Rotor leakage factor is generally taken zero. $\Psi(n)$ and $\Psi(n-1)$ are the value of rotor flux angles at nth and $(n-1)$th instants, respectively, and ΔT is the sampling time which can be taken as 100 μs for our considerations.

These currents (i_{sd}^*, i_{sq}^*) are in synchronously rotating reference frame and now these are converted to stationary reference frame three-phase currents (i_{as}^*, i_{bs}^*, i_{cs}^*) as

$i_{as}^* = -i_{sq}^* \sin\Psi + i_{sd}^* \cos\Psi$

$i_{bs}^* = [-\cos\Psi + \sqrt{3}\sin\Psi]\, i_{sd}^*(1/2) + [\sin\Psi + \sqrt{3}\cos\Psi]\, i_{sq}^*\,(1/2)$

$i_{cs}^* = -(i_{as}^* + i_{bs}^*)$

where i_{as}^*, i_{bs}^*, and i_{cs}^* are the three-phase reference currents. These three-phase reference currents generated by the vector control are compared with that sensed motor currents ($i$as, $i$bs, and $i$cs). The calculated current errors are

$i$ke = $i$ks* − $i$ks, where $k = a, b, c$.

These current errors are amplified and then fed to the pulse width modulation current controller, which controls the on and off times of different switches in Voltage source inverters. The VSI generates the PWM voltages are now fed to the motor to develop the desired torque for running the motor at a required speed under given loading conditions.

7.3.3 FFT Analysis of Vector Controlled Induction Motor Drive

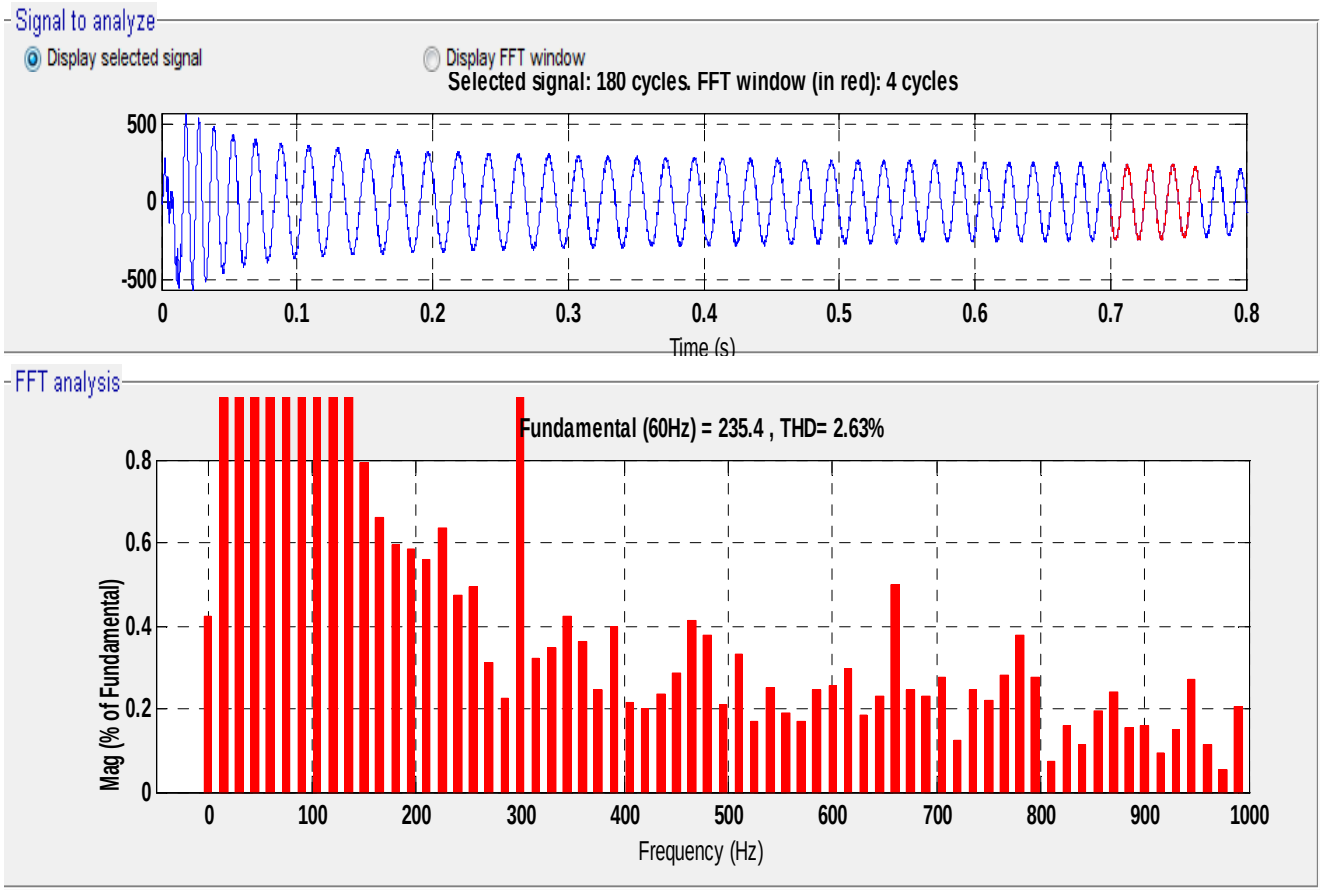

Fig 7.9 Fast Fourier transform of Vector Control of Induction motor drive

CHAPTER-8

CONCLUSION AND FUTURE WORK

A comparative analysis of Total harmonic distortion by Pulse width modulation fed inverter and vector control method is proposed in this thesis. In this study, the individual mathematical model for each component was developed in Matrix laboratory and the model , simulation and control of systems was developed using simulation. The work was expected to provide guidelines for finding total harmonic distortion for current and voltage.

The results of simulation has shown that the system performance is excellent and the mathematical models and control techniques developed in this thesis can also be used to design and control the other different topologies of adjustable speed drives.

The issue of power quality is becoming very apparent due to the increasing number of non-linear loads. The low frequency harmonic current produced by such loads can cause damage to the power system equipments. Adjustable speed drive (ASD) is becoming a powerful load component for power distribution. It is important to design such type of loads to reduce the problems coming from harmonic pollution. This paper involves simulation of Adjustable speed drive such that power quality is significantly corrected. The detailed results has been noted and analyzed in chapter-7 with proper justification .In the view of that, future scope aims to develop a better electrical and mechanical performance which can effectively improve the dynamic stability, transient response of systems during faulty grid conditions and also it provides a better working conditions for fan type load, winding machines etc.

Phase	PWM Inverter(%)	Vector Control (%)
A	28.14	2.63
B	27.4	4.16
C	28.15	2.61

Fig.8.1THD comparison by two methods

The most important thing is that speed becomes constant earlier in vector control method rather than PWM inverter fed Induction motor.

APPENDICES

Induction Motor Ratings

50 HP , 460 V ,1480 rpm, 60 Hz

L_m= 0.02711 H ,L_r=0.000724 H R_r= 0.0503 Ω R_s=0.02233 Ω L_s=0.000724 H

Pulse Width Modulation

Switching frequency=2000

Modulation Index=0.4

DC Supply= 780 V

Vector Controlled Induction Motor Drive

PI Controller K_p= 2 K_i= **26**

Current Controller 20 db

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- Shravani Mathur, Vikas Kumar "Calculation of total Current harmonic distortion by PWM method for permanent magnet synchronous motors " in International journal of engineering and research application" Issue 3, Volume-3, ISSN no.2248-9622 www.ijera.com
- Shravani Mathur, Vikas Kumar , Ritika Verma " Calculation of total harmonic distortion by PWM method for Induction motors" in National conference on "Modeling and simulation of Electrical systems-2013(MSES-2013)
- Shravani Mathur, Ritika Verma "Comparative study of total harmonic distortion on the current waveform by PWM fed and Vector Controlled Permanent magnet synchronous motors" in International Conference on Advancements in engineering, pharmacy, management and science Feb-2014
- Shravani Mathur, Vikas Kumar "Analysis of total harmonic distortion on the current waveform on the Induction motor drive" in National Conference on Recent Advancement in Futuristic Technologies (NCRAFT-2013)

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INTRODUCTION Adjustable Speed drives are needed in various applications. The application of adjustable speed drive will lead to the harmonics present in the current. It creates power grid pollution and it also leads to electromagnetic interference into the atmosphere. Quality of power and electromagnetic interferance are the main constituents of electrical Induction motor drives. Such loads are distributed over an electrical network. Harmonics are not desirable as this type of interference with electrical equipments will result in unacceptable level of distortion of voltage.

Harmonic calculations needs unique equipments, which are quite expensive and they are not easily available in the market .My paper investigates the modeling and simulation of an induction motor for an adjustable speed drive and the analysis of harmonics was also done here. Using ac drives and ac motors have the plus point of lesser maintenance, more speeds and lesser size. When compared to direct current drives, the higher cost of alternating current drives is compensated by an ac machine which is quite lower in comparison to dc machine.

When compared to uncontrolled alternating current motors which is supplied by a power grid, the effectiveness of the inverter controlled drives can be increased by using flux optimization he simulation of Adjustable speed drives can be done by two methods for calculating Total Harmonic Distortion i.e.Pulse width modulation fed induction machine and by the use of vector controlled inction motors The resulting energy saving, which depends on the respective application, may be beneficial for the power system. Adjustable speed drives tells us about the apparatus which are used to control the speed .

When the speed is selected from various preset values , the drive is called adjustable speed drive An adjustable speed drive consists of a motor and a regulator for regulating the operating speed. The union of a constant speed motor and adjustable speed varying device can be also called ASD Power electronics based variable frequency drives are rapidly making older technology obsolete. 1.2.1 Induction motor can be operated in one direction or both the directions.

It depends upon the necessity of drives Per-phase equivalent circuits are mostly in use in steady-state method and designing of an ac machines which are not suitable to get the dynamic performance of the

motor.A dynamic model is necessary to analyze vector control of ac motor drives A big goal was achieved in the study of three-phase ac machines through the development of the reference frame theory.

The machine model can be transformed from one to another reference frame by using these techniques It is quite possible to give the simplicity to the complexity of mathematical induction machine model by choosing the refererance frame theory In earlier days, these techniques were invented for the analysis and simulationof ac machines, but nowadays they are being rapildly used in the digital control of those machines. The necessity for compact machine models is there as digital control tehnology is used to control torque ,current and flux of ac motors.

The induction motor is mostly used in the industries because of its self starting feature, lower cost,reliable and rugged structure these motors are generally used where fast dynamic response is not necessary With the application of vector control it is possible to control the induction motors to achieve dynamic performancecomparable to that of dc motors The dynamic model of Induction machine is necessary because it helps to understand the vector control. The torque -speed charecterstics are easily explained by the dynamic model equations which are created on rotating reference frame 1.2.2

Operation of Induction motor Induction motor is also a part of controlled speed drive configruation 1nduction Machine is fed from power electronics converter (PEC), but it is also indirectly fed from power grid in various cases Induction machine has smooth operation because of its robustness. There are two types of Induction motor depending upon its rotor construction These are Squirrel Cage and Wound rotor motor or slip ring machine. The work of this thesis depends on working of squirrel cage Induction Motors.

The operation of induction motors is based on electromagnetic induction Squirrel Cage rotor has copper bars and electromotive force and torque produced due flux changing in stator magnetic field and due to

Adjustable speed drive (ASD) is becoming a very useful load component for supply distribution. It is important to design such type of loads to reduce the problems coming from harmonic pollution. This paper investigates the simulation of Adjustable speed drive such that power quality is corrected upto an extent. The detailed results has been noted and analyzed in chapter-7 with proper justification .Taking this into the consideration, future scope aims to design a quite better electrical and mechanical performance system which can easily improve the dynamic stability and the transient response of systems during faulty grid conditions and also it provides a better working conditions for fan type load, winding machines etc.
Phase PWM Inverter(%) Vector Control (%) A 6.4 5.7 B 6.7 5.3 C 6.8 5.2 Fig.8.1THD comparison by two methods The most important thing is that speed becomes constant earlier in vector control method rather than PWM inverter fed Induction motor. APPENDICES Induction Motor Ratings 50 HP , 460 V ,1480 rpm, 60 Hz Lm= 0.02711 H ,Lr=0.000724 H Rr= 0.0503 ? Rs=0.02233 ? Ls=0.000724 H Pulse Width Modulation Switching frequency=2000 Modulation Index=0.4

DC Supply= 780 V Vector Controlled Induction Motor Drive PI Controller Kp= 2 Ki= 26 Current Controller 20 db

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